Amplitude and phase characterization of weak blue ultrashort pulses by downconversion

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We present difference-frequency generation cross-correlation frequency-resolved optical gating, a new method of characterizing the amplitude and phase of weak ultrashort pulses in the blue spectral region. The method uses the spectrally resolved downconversion signal of the blue pulse and a fully characterized reference pulse with a lower center frequency. The amplitude and phase of the blue test pulse are retrieved from the corresponding spectrogram and electric field of the reference pulse with an interactive Fourier-transform algorithm. © 1999 Optical Society of America

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The technique of frequency-resolved optical gating (FROG), which is based on the spectrally resolved correlation signal of two identical copies of the pulse, has proved to be a reliable method for the characterization of the amplitude and phase of ultrashort optical pulses in many applications.[1–4] However, there are certain circumstances for which this normal FROG technique is not suited. One example is pulses that are so weak that they cannot even be retrieved by second-harmonic generation frequency-resolved optical gating (SHG FROG),[5] the most-sensitive FROG geometry. To solve this problem we recently suggested a cross-correlation technique that we call cross-correlation frequency-resolved optical gating[6] (XFROG), which uses the pulse to be characterized (the test pulse) and a fully characterized intense reference pulse. XFROG is more advantageous than spectral interferometry[7] because it does not need spectral overlap between the reference and the test pulses.

Another example of pulses that cause problems for the normal FROG technique are ultrashort blue pulses with weak pulse energies. These pulses are normally generated by frequency doubling or tripling of pulses in the near IR. Although the fundamental pulses can be characterized with one of the FROG geometries,[5,8] it is not possible to extend these techniques straight to the blue spectral region, mainly because of the fact that the corresponding correlation signals have at least twice the center frequency of the blue test pulse.[9] Therefore, several problems occur: First, most nonlinear crystals are not transparent in the deep UV. β-barium borate (BBO), for example, is transparent only down to 185 nm, allowing analysis only of pulses with wavelengths no shorter than 370 nm. Additionally, phase matching in this spectral region causes severe problems with most nonlinear crystals. Also, the UV detectors and the special UV optics that are required for recording of the FROG spectra are inconvenient, as they normally do not exist in many labs.

We show in this Letter that it is advantageous to use a cross-correlation technique that in this case utilizes the fundamental pulse as the fully characterized reference pulse. It is then possible to apply difference-frequency generation (DFG) as a nonlinear process and thus avoid the aforementioned problems. We call our method difference-frequency generation cross-correlation frequency-resolved optical gating (DFG XFROG).

The experimental setup for DFG XFROG characterization of the second-harmonic output of a femtosecond Ti:sapphire laser is shown in Fig. 1(a). A beam from a Coherent MIRA 900 Ti:sapphire laser oscillator operating at $\lambda_0 = 800$ nm was first characterized with standard SHG FROG. To create the blue test pulse we doubled the main part of the beam in a 0.9-mm-thick BBO crystal, using type I phase matching. The pulse energies of the blue pulses were near 60 pJ. The second part of the Ti:sapphire laser beam was used as a reference pulse and was passed through a variable time delay. The blue test pulse and the reference pulse were focused by a 120-mm focusing lens under a small angle into a 300-μm BBO crystal. The difference-frequency signal was generated by type II phase matching[10] and imaged with a focusing lens onto the entrance slit of the spectrometer. An OG 590 Schott filter was used to block stray light from the blue test pulse, which would be superimposed in second diffraction order onto the spectrogram. Subtraction of a constant background eliminates the stray light contribution from the reference pulse.

The electric field of the DFG XFROG correlation signal has the form

$$E_{\mathrm{Sig}} \propto E_{\mathrm{Test}}(t) E^{*}_{\mathrm{Ref}}(t - \tau)\,, \tag{1}$$

with a center frequency $\omega_{\mathrm{Sig}} = \omega_{\mathrm{Test}} - \omega_{\mathrm{Ref}}$. The squared magnitude of the spectrum of the DFG signal

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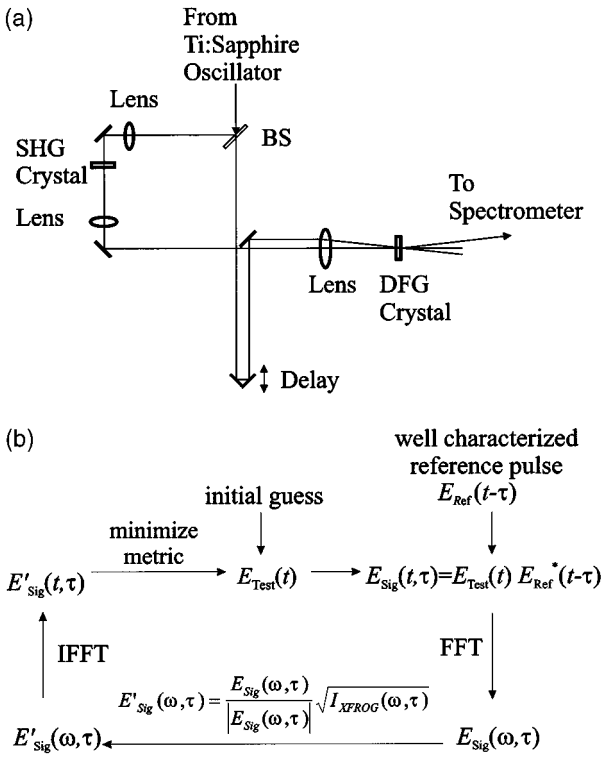

Fig. 1. (a) Experimental setup for DFG XFROG measurements: BS, beam splitter. (b) Schematic of the DFG XFROG algorithm.

recorded as a function of delay τ between the two pulses yields the DFG XFROG trace:

$$I_{\mathrm{XFROG}}(\omega,\tau) \propto \left| \int_{-\infty}^{\infty} \mathrm{d}t E_{\mathrm{Test}}(t) E_{\mathrm{Ref}}^{*}(t-\tau)\exp(i\omega t) \right|^2 . \tag{2}$$

To retrieve the unknown blue test pulse we implemented an iterative Fourier-transform algorithm with generalized projections[12] [see Fig. 1(b)]. The DFG XFROG algorithm needs the experimentally measured DFG XFROG trace $I_{\mathrm{XFROG}}(\omega,\tau)$ and the retrieved electric field of the reference pulse $E_{\mathrm{Ref}}(t-\tau)$ as input data. The first generalized projection is done by replacement of the magnitude of the guessed signal field $E_{\mathrm{Sig}}(\omega,\tau)$ by the square root of the intensity $I_{\mathrm{XFROG}}(\omega,\tau)$. For the second generalized projection, we define a distance metric

$$Z = \sum_{i,j=1}^{N} \left| E'_{\mathrm{Sig}}(t_i,\tau_j) - E_{\mathrm{Test}}(t_i) E_{\mathrm{Ref}}^{*}(t_i-\tau_j) \right|^2 \tag{3}$$

and minimize Z with respect to $E_{\mathrm{Test}}(t)$. The reference pulse is kept unchanged during the second generalized projection. To monitor the progress of the algorithm we use the FROG error G defined in Ref. 13. An important feature of the DFG XFROG algorithm is its tolerance against retrieval errors in the electrical field of the reference pulse. Numerical simulations have shown that deviations in the reference pulse from the correct field lead to uncertainty in the retrieved test pulse, which is of the same order as the input error. For example, increasing the pulse length of a Fourier-limited Gaussian reference pulse by 15% yields a pulse with a length that is 87% of the original linearly chirped Gaussian test pulse. The phase is kept almost unchanged, and the shape is still Gaussian.

DFG XFROG offers the same advantages as the normal XFROG technique. It is possible to characterize weak blue test pulses by the use of a strong reference pulse because according to relation (1) the electric field of the DFG XFROG correlation signal is proportional to the electric field of the reference pulse. Also, there exists no temporal ambiguity in the retrieved pulse shape, since the trace is usually not symmetric with respect to the delay τ (see Fig. 2). Some attention has to be paid when one is using SHG FROG to characterize the reference pulse because of the time ambiguity of this FROG geometry. However, the direction of time in reference pulses characterized by SHG FROG can normally be determined by the techniques described in Ref. 5. Additionally, inserting the time-reversed complex-conjugate reference pulse into relation (1) yields a signal field that does not match the experimental data and hence leads to a large error in the DFG XFROG algorithm.

It is in principle possible to implement a technique such as twin recovery of electric-field envelopes by the use of FROG (TREEFROG),[14] which retrieves two difference pulses from only one trace by blind deconvolution. However, blind deconvolution is a much more difficult problem than retrieving just one pulse and is prone to failure in the presence of noise and very weak signals. The DFG XFROG concept of using a known reference pulse is certainly a major advantage under these circumstances.

The reference pulse used in the DFG XFROG algorithm was characterized by SHG FROG. The pulse was retrieved well, with a FROG error of 0.0023 for a 128×128 pixel trace. The FWHM of its intensity is $\tau_p = 168$ fs, and the FWHM of the spectrum is $\Delta\nu = 3.1$ THz. The corresponding time–bandwidth product of 0.52 can be explained by higher-order residual distortions, which were not compensated for.

To check our method we analyzed two different blue femtosecond pulses near 400 nm that were generated

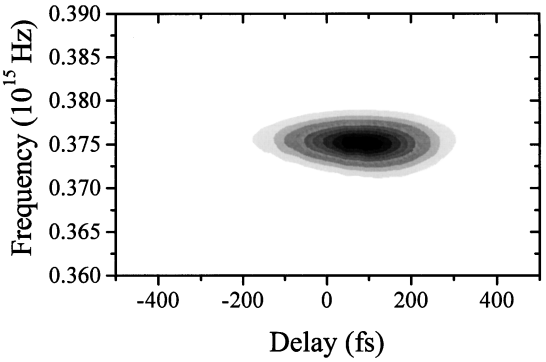

Fig. 2. Experimentally measured DFG XFROG trace of a blue pulse that was created by SHG of a pulse from a Ti:sapphire oscillator. The fundamental pulse was used as the reference pulse. The DFG XFROG trace is shown as a density plot with ten equidistant steps from zero intensity (white) to maximum intensity (black).

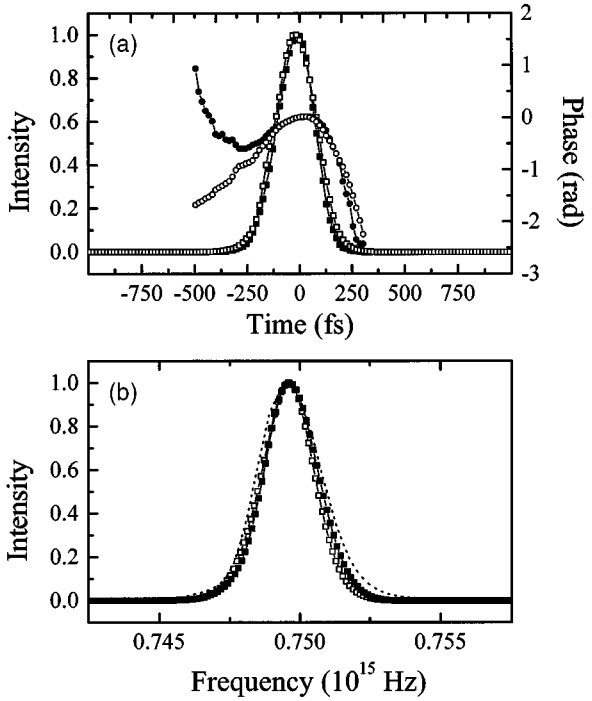

Fig. 3. (a) Intensity (■, unchirped pulse; □, intentionally chirped pulse) and phase (●, unchirped pulse; ○, intentionally chirped pulse) as a function of time of the retrieved blue test pulses. (b) Experimentally measured (···) and calculated (■, unchirped pulse; □, intentionally chirped pulse) spectra of the blue test pulse.

in the BBO crystal that were either unchirped or intentionally chirped by propagation through 2.54 cm of BK7 glass. The final FROG errors of the DFG XFROG algorithm for 128 × 128 pixel traces were $G = 0.0036$ for the unchirped pulse and $G = 0.0057$ for the intentionally chirped pulse. Figure 3(a) shows the retrieved temporal intensity and phase of the pulses. Owing to the influence of the glass, the pulse width broadened from $\tau_p = 211$ fs to $\tau_p = 239$ fs. Figure 3(b) shows the measured and the retrieved spectra of the blue pulses, and the agreement between experiment and calculation is quite good. The calculated bandwidth for both pulses is $\Delta\nu = 2.2$ THz, compared with a measured bandwidth of $\Delta\nu = 2.7$ THz. The difference can be explained by group-velocity mismatch[15] of the fundamental and the second-harmonic pulses in the nonlinear crystal, which acts as a spectral filter and hence leads to a spectral width of the retrieved pulse that is too small.

For shorter pulses a thinner crystal is required for DFG because then the influence of group-velocity mismatch is reduced. In this case, we suggest rotating the polarization of the reference pulse by 90° to use type I phase matching for DFG. It is then possible to remove stray light from the reference pulse with a polarizer, and therefore a better signal/noise ratio is obtainable, which is important for weak DFG signals.

In conclusion, we have demonstrated a powerful method for characterizing weak ultrashort pulses in the blue spectral region. Recording the cross-correlation spectra created with downconversion and by use of the DFG XFROG amplitude and phase-retrieval algorithm,[16] we avoid the problems connected with UV optics when using SHG FROG.

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